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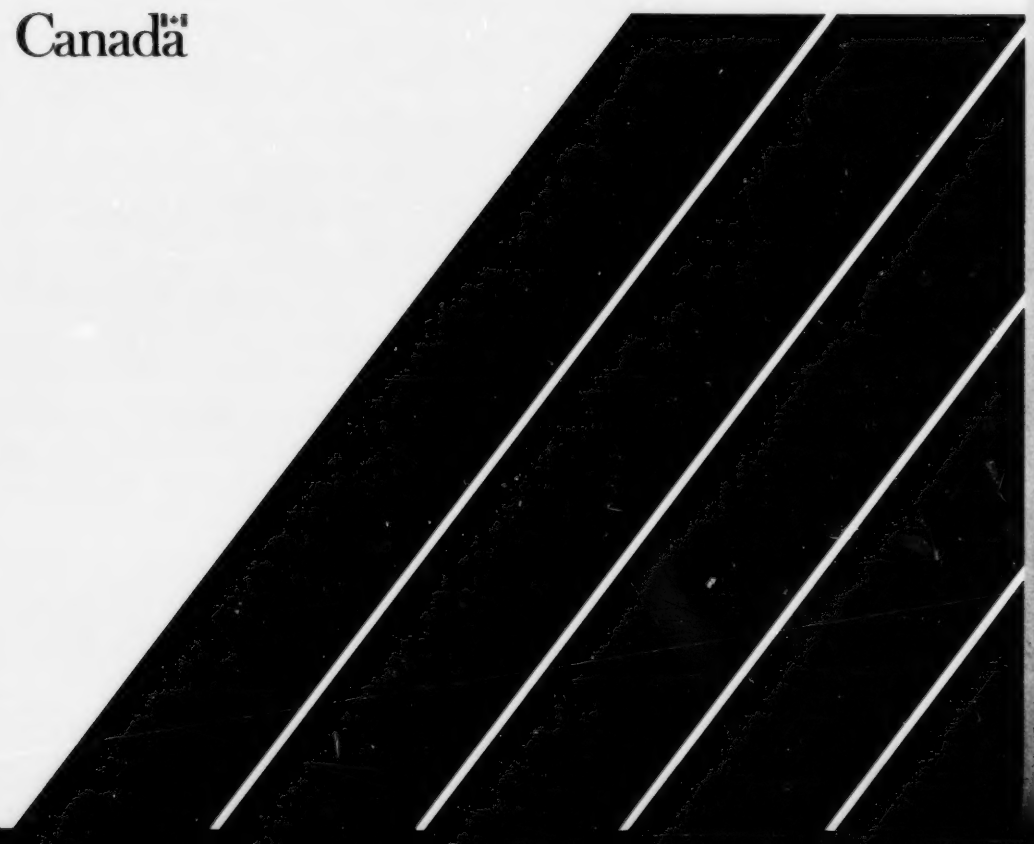

COMMISSIONING OF THE 20-L VESSEL FOR STUDYING DUST-AIR EXPLOSIONS

K.J. Mintz

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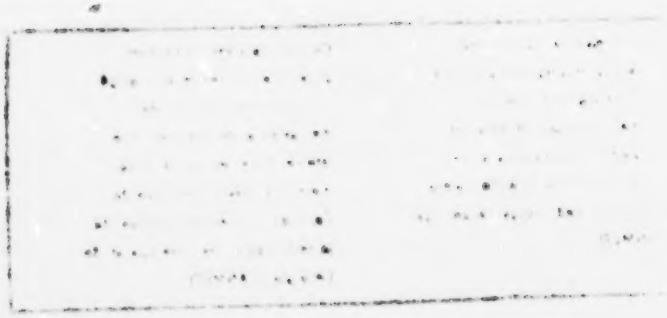

COMMISSIONING OF THE 20-L VESSEL FOR STUDYING DUST-AIR EXPLOSIONS

by

K.J. Mintz*

ABSTRACT

A 20-L vessel, based on the U.S. Bureau of Mines design, has been installed in the dust explosion laboratory of the Canadian Explosive Atmospheres Laboratory as its new standard apparatus for dust explosions. A systematic study has been carried out to determine the experimental factors that can affect the accuracy of the results. Lycopodium powder was used as the "standard" material. One key factor is the air pulse used to disperse the dust and bring the vessel to the desired pressure. Explosion pressure was found to vary linearly with the initial pressure. The problem with lack of reproducibility of the maximum rate of pressure rise was shown to be due to its high dependence on the degree of turbulence. The Sobbe chemical ignitor yielded the same explosion pressures as the electric arc at high concentrations, but extended the range of explosibility to lower concentrations, hence it must be used for minimum explosible concentration determinations. The minimum oxygen concentration for lycopodium explosions was also determined.

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KEYWORDS: dust explosions, lycopodium, 20-L vessel

MISE EN SERVICE DU RECIPIENT DE 20-L POUR L'ETUDE DES EXPLOSIONS DE POUSSIERE DANS L'AIR

par

K.J. Mintz*

RESUME

Un récipient de 20 L, basé sur le modèle de l'U.S. Bureau of Mines, a été installé au laboratoire des explosions de poussière du Laboratoire canadien des atmosphères explosives où il sera le nouvel appareil étalon pour les explosions de poussière. Une étude systématique a été effectuée pour déterminer les facteurs expérimentaux qui peuvent influer sur l'exactitude des résultats. De la poudre de lycopodium a été utilisé comme matériau "étalon". Un facteur clé est l'impulsion d'air utilisée pour disperser la poussière et porter le récipient à pression désirée. On a constaté que la pression d'explosion est une fonction linéaire de la pression initiale. Le problème de manque de reproducibilité de la vitesse maximale d'élévation de la pression semble tenir au fait qu'elle dépend étroitement du degré de turbulence. L'allumeur chimique Sobbe a produit les mêmes pressions d'explosion que l'arc électrique aux concentrations élevées, mais semble élargir la plage d'explosibilité aux faibles concentrations, de sorte qu'il faut l'utiliser pour déterminer les concentrations minimales. La concentration minimale d'oxygène pour produire un explosion du lycopodium a aussi été déterminée.

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MOTS CLES: explosions de poussière, lycopodium, récipient de 20-L

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INTRODUCTION

The Hartmann apparatus has been used for many years as the standard one for studying dust-air explosions (1). As the knowledge of explosion phenomena increases, the limitations of this apparatus have become more and more apparent, specifically, the small size, the cylindrical shape, the leakage, and, most importantly, the non-homogeneity of the dust dispersion. To overcome all these problems, Bartknecht has developed a 1 m^3 vessel which is described in an International Standard (2,3). The logistics of using that large a vessel makes the cost of carrying out a series of tests nearly prohibitive. Moreover, there is some indication that the dispersion method does not disperse all the dust placed in it. Thus the nominal concentration may be greater than the actual. As an alternative, the U.S. Bureau of Mines has developed a near-spherical 20-L vessel, which they believe is sufficiently large so as not to have any problems with scaling up the results to real-life situations, yet is small enough that it remains a practicable laboratory apparatus (4).

MRL purchased a 20-L vessel constructed to the USBM design and installed it in its dust explosion laboratory. It is intended both for routine tests carried out for cost-recovery and for research purposes. The procedure for using it has been given in a separate report (5).

The purpose of this report is to describe a series of explosion tests carried out on lycopodium powder which was used as a "standard" material to evaluate the 20-L vessel.

APPARATUS

The 20-L vessel was designed by the U.S. Bureau of Mines and built by Safety Consulting Engineers, Rosemount, IL. Several modifications were made to it here prior to using it (see Figs. 1 and 2). The lid of the vessel was originally held in place by a hinge. This was replaced by a pair of handles so that the lid could be lifted straight up. A pulley system with a locking device was installed to make it easy to lift it. Teflon electrode holders, similar to those used in the Hartmann, were made to enable easy removal and adjustment of the spacing of the electrodes. Special fittings were made for wires to be fed through the wall of the vessel, for attachment to the leads of the chemical ignitor. A holder was built for the chemical ignitor so that it could be held rigidly in the centre of the vessel. A port was made for the strain-gauge pressure transducer. The diaphragm of the pressure transducer is about 3 cm from the end of the fitting, so that the flame front from the explosion will cool down before it reaches the diaphragm and thus not damage it.

An Edwards Model E2M8 vacuum pump with a 1TF20K inlet dust filter is used for evacuating the 20-L vessel. It takes less than 3 minutes to go from atmospheric to 1 kPa. The leak rate of the 20-L vessel is less than 2 kPa/hour, when the vessel is under full vacuum.

A schematic of the entire apparatus is shown in Fig. 3. The 16 L air chamber is filled with air or other gas mixture, which is released quickly by the solenoid valve through the dust chamber into the 20-L vessel. The explosion control panel controls the timing of the air dispersion and ignition of the explosion. The signal from the strain-gauge pressure transducer (CEC 1000 or 5000) is amplified and conditioned by the

strain-gauge control unit before being fed into the Nicolet 4094 digital oscilloscope. The electronics are fully described elsewhere (6).

An oxygen analyzer has been installed to enable the determination of the extent of reaction following a test (7). It can also be used to analyze a nitrogen/oxygen mixture prepared in the 16 L air chamber, for tests to be done in either oxygen enriched or deficient atmospheres.

The infrared spectrometer is used to measure the quantity of gaseous combustion products in those cases in which they are of interest, for example, sulphur dioxide resulting from the explosion of sulphide ore dusts.

RESULTS

Air Only

A large number of tests were carried out with the solenoid valve from the air chamber open for varying lengths of time. The 20-L vessel was evacuated before each test. The purposes were: (1) to determine the characteristics of the air pulse; (2) to determine the reproducibility of the air pulse; and (3) to determine the time required to produce exactly one atmosphere pressure inside the vessel at the end of the pulse.

Figure 4 shows the complete pressure traces for three different solenoid open times. The vertical axis is expanded by a factor of four compared to explosion tests. The most striking feature is that the pressure, after reaching a maximum, decreases steadily (in the timeframe of the graph). Actually, after about 20 s, the pressure stabilized about 16% below the maximum value.

To determine the cause of that phenomenon, a thermocouple was installed in the 20-L vessel to monitor the temperature. It was connected to

an Omega analogue converter (which outputs 1 mv/°C) which in turn was connected to the second channel on the Nicolet digital oscilloscope. Thus, a temperature-trace was produced simultaneously with the pressure-trace curve (see Fig. 18). Because the thermocouple has a significantly slower response than the pressure transducer, the actual temperature response may be somewhat steeper than that indicated and the maximum temperature may not have been detected. Nevertheless, the observed temperature increase of 10.6°C is significant. The slow decrease in temperature after two seconds is probably due to the re-establishing of thermal equilibrium with the walls of the vessel.

If one assumes that the ideal gas law holds, then, since the number of moles of gas remains constant inside the vessel after the end of the pressure pulse, the temperature T (in °K) of the gas at any time should be equal to $T_f \cdot P_f/P$, where the subscript f refers to the final conditions. For the standard pressure pulse, the maximum temperature rise should have been about 80°C. Even considering that the thermocouple cannot follow a rapidly changing temperature, it seems doubtful that such a large temperature increase actually occurred. The ideal gas law is based on equilibrium conditions; under the conditions of this test, it is quite likely that the equilibrium approximation is invalid.

In order to show that the above results were not a peculiarity of the pressure pulse, a simpler test was carried out. First, the 20-L vessel was evacuated. During this evacuation, the temperature of the gas remaining inside the vessel decreased steadily from 21°C (room temperature) to 15°C. Then, air was allowed to enter slowly from the atmosphere through a plug valve over 59 s. The pressure and temperature data were collected as before on the Nicolet digital oscilloscope and shown in Fig. 19. Note that the time

scale is now 20 s/division. The pressure drop after the maximum (which occurred when the valve was closed) was 2%. The temperature rise of 7°C was smaller than the test above in which the same quantity of air entered in only 0.3 s.

Since the explosion parameters depend significantly on the pressure at the time of the explosion, (see below) it is important to know whether this phenomenon will have a significant effect on the results. Generally, the dust cloud is initiated about 0.1 s after the end of the air pulse, and never more than 1 s later. The change in pressure during this time will be less than 3%. To reduce the imprecision further, the pressure at the time of ignition should be used as the initial pressure, rather than the maximum pressure which occurs at the end of the air pulse. The estimated uncertainty in the explosion pressure and rate of pressure rise due to the uncertainty in pressure will be of the order of 1%, which is much less than the standard deviation from identical tests.

According to Wiemann (8), the maximum explosion pressure decreases with increasing temperature, being linear with the reciprocal of the absolute temperature. This relationship is probably due to the decreasing quantity of oxygen per unit volume at higher temperatures, in accordance with the ideal gas law; hence, the amount of reaction is decreased proportionately. On the other hand, the rate of pressure rise is not a significant function of temperature. The rise in temperature indicated above would decrease the explosion pressure by about 4%, about the same as the standard deviation of identical tests on lycopodium (see below). Hence, this phenomenon may be the limiting factor for precise tests on explosion pressure. For most dusts, inhomogeneity of particle size, composition and shape will cause greater scatter of data.

A more detailed examination of the initial portion of the pressure traces of Fig. 4 can be made from Fig. 5, in which the horizontal axis is expanded by a factor of four. The small spikes on two of the curves are caused by electrical noise from the relay controlling the solenoid. The pressure starts to rise about 78 ms after the solenoid starts to open and stops rising about 78 ms after the solenoid is closed. This delay is due to the time required for the air to travel from the solenoid through the tube and reach the pressure transducer. It can be seen that the pressure increase for the shortest t_s (the solenoid open time) curve is linear with time; for increasing t_s, the curve progressively bends away from the straight line. The reason is that for small t_s, the pressure in the air tank can be considered constant; for increasing t_s, the pressure drop becomes more significant. For t_s = 310 ms, the pressure drops from 1100 to 960 kPa. By comparison, the air chamber for the Hartmann apparatus is only 50 cm^3; during a test with that apparatus, the pressure in the air chamber drops from 690 kPa to 120 kPa.

The maximum pressures reached for all the "blank" trials (i.e. those in which no dust was present) were plotted against t_s (see Fig. 6). Up to about 400 ms, the pressure is a linear function of the solenoid open time (the line shown is a linear least-squares for all points below 400 ms); but above 400 ms, the pressure becomes increasingly lower than the linear relationship predicts. The cause is that the decrease in the pressure in the air chamber becomes increasingly significant, thus there is not a constant pressure source. Fig. 6 is useful for determining the appropriate settings for studying explosibility at different pressures. Most work, however, will be carried out at one atmospheric pressure, which requires a t_s of about 310 ms. The 5 trials at that t_s yielded 100.5 $\pm$ 0.2 kPa. Hence, the

initial pressure, i.e. the pressure at which the dust-air mixture is ignited, is controlled to better than 1%. In the Hartmann apparatus, the pressure at which the dust-air mixture is ignited ranges from about 15 to 48 kPa above atmospheric. Since the explosion pressure is roughly proportional to the initial pressure (see below), this effect can cause significant error in Hartmann tests.

The selection of 1100 kPa for the pressure in the air tank was made so as to be consistent with the USBM. Decreasing this pressure increases the t_s required to have a one atmosphere initial pressure in the 20-L vessel, e.g. 600 ms was required with 690 kPa. Since better dust dispersion occurs with shorter pulses, all tests will be carried out at the maximum practicable pressure of 1100 kPa.

When dust is in the sample container in the 20-L vessel, the pressure achieved for a given t_s is slightly lower, because the air must flow through the container before entering the 20-L vessel and thus there will be a small back pressure. Hence, the t_s must be increased, depending on the quantity of dust in the chamber and its density. For example, 10 g of lycopodium (which yields a concentration of 500 g/m^3) requires that the t_s be increased by about 10 ms. The particular value of t_s must be determined empirically for each material, though, in most cases, an estimate will give an initial pressure within the acceptable range of 95 - 105 kPa.

Lycopodium - Reproducibility of Explosion Tests

A typical pressure trace for lycopodium at a concentration of 500 g/m^3, a t_s of 320 ms and a delay time of 100 ms is shown in Fig. 7, along with its derivative curve. The course of events can be observed through the window of the 20-L vessel. The dust cloud is formed near the beginning of

the air pulse; the turbulent nature of the dust cloud can be seen briefly; then a bright flash occurs when the dust-air mixture explodes. The graph of the pressure trace is used only for illustrative purposes; the actual parameters are calculated from the digital stored waveform. The spikes arising from the relay closing the solenoid valve and the relay starting the arc discharge can be seen on the traces. The pressure starts to rise about 25 ms after the latter event. Part of that time may be a true induction time, and part of it is the time for the pressure front to reach the pressure transducer.

In the Hartmann apparatus, the electrode discharge is struck before the dust is dispersed. The point on the pressure trace at which the explosion starts cannot be determined accurately, in most cases, because the air pulse is still entering the chamber when the dust cloud ignites. This creates uncertainty in both the time and pressure measurements.

A total of 10 tests were carried out under the same conditions as specified in the previous paragraph. The measured parameters are given in Table 1. The standard deviations are significantly smaller than those determined in similar tests carried out in the Hartmann apparatus. The t_r/t_m ratio indicates where the maximum rate of pressure rise occurs; this is later for the 20-L vessel than for the Hartmann. The reason may be attributed to a more inhomogeneous dust mixture in the Hartmann; the explosion is initiated in a higher concentration region and propagates into a lower concentration region.

Two of the ten tests were carried out with lycopodium that had been dried at 80°C for 16 hours. For the Hartmann tests, drying had increased P_m and $(dP/dt)_m$ substantially; for the 20-L tests, drying had little effect. It would seem most probable that the effect of drying lycopodium was

not to increase the reactivity of the dust-air mixture,but rather to allow better dispersion. The higher pressure of air used to disperse dust in the 20-L vessel would appear to have been sufficient to overcome any problem with particles sticking together.

Lycopodium - Effect of Initial Pressure

The effect of initial pressure on the explosion parameters was determined by varying t_s at a constant concentration of 500 g/m^3. The delay time to start the discharge from the electrodes was maintained at 100 ms after the end of the pressure pulse. The results show that the explosion pressure is quite linear with respect to initial pressure in this pressure range (see Fig. 8). The rate of pressure rise data is much more scattered, though there does not seem to be any systematic deviation from linearity (see Fig. 9). The reason for the linear relationship is that explosion pressure is primarily a function of the total amount of reaction. Dust explosions are strongest on the fuel-rich side of stochiometry; thus the amount of reaction is proportional to the quantity of oxygen present, which in turn is proportional to the pressure.

Wiemann (8) has recently published work on the pressure dependence of brown coal in the 1 m^3 vessel at 40°C. Ignition was by two 5 kJ pyrotechnic ignitors. No indication whether or not the pressure due to the chemical ignitors was taken into account (see below). He obtained a linear relationship between explosion pressure and initial pressure (up to 4 bar) and rate of pressure rise and initial pressure (up to 3 bar).

The tests in the previous section were actually carried out at slightly below atmospheric pressure; these can now be corrected to atmospheric pressure. The explosion pressure is increased by 3% to 550 kPa;

the rate of pressure rise is also increased by 3% to 13.9 MPa/s. These corrections in this case are less than the standard deviations and therefore are not too important. It can be seen, however, that it is important, if accurate values are to be obtained, to ensure that the initial pressure is as close to atmospheric as possible. It should also be noted that normal variations in atmospheric pressure will have some effect on the explosibility. (The tests carried out in the 20-L vessel are based on absolute pressures, so that the results are independent of the actual atmospheric pressure during the test.)

As mentioned above, tests in the Hartmann are actually carried out above atmospheric pressure. For example, we measured P_m for 500 g/m^3 of lycopodium to be 637 ± 66 kPa, substantially greater than the value obtained in the 20-L vessel. The pressure at the time of ignition in the Hartmann was, however, 25 kPa above atmospheric. If the correction for pressure is applied, P_m is decreased to 487 kPa, less than the 20-L vessel value of 550 kPa, but now within the experimental uncertainty. The $(dP/dt)_m$ is a function of vessel size; for spherical or near spherical vessels, $(dP/dt)_m$ is proportional to volume$^{-1/3}$. Thus, the value of $(dP/dt)_m$ obtained in the Hartmann, 54 ± 9 MPa/s, is equivalent to 21 MPa/s in a 20-L vessel. Correcting to atmospheric pressure, $(dP/dt)_m$ becomes 18 MPa/s, within experimental uncertainty of the 20-L vessel value of 13.9 MPa/s.

Effect of Delay Time

When the air pulse disperses the dust, considerable turbulence is imparted to the dust. This turbulence decreases over time; at the same time, settling due to gravity will begin. Both effects will be dependent on the density and particle size of the particular dust sample. Cashdollar and

Hertzberg (4) have shown that no significant settling of coal dust occurs in the first second after the air pulse. They recommend, for routine studies, a 100 ms delay time before igniting.

Explosion tests were carried out on lycopodium dust at a concentration of 500 g/m^3 using the electrodes with t_s = 310 ms (which produces one atmosphere pressure). The delay set time was varied over the range 0 - 720 ms (the maximum possible with the present control panel). The actual interval time between the end of the air pulse and the beginning of the explosion was used rather than the value set on the control panel. (The former is 10 - 40 ms longer.) Explosion pressure decreases slowly with increasing delay time up to about 200 ms (see Fig. 10). This decrease is caused by the decrease in the level of turbulence. In this region only a small amount of lycopodium does not react. Between 200 and 300 ms, P_m decreases more rapidly to reach a near plateau, which lasts until about 600 ms. A considerable amount of lycopodium does not react under these conditions. In this region, there is probably little turbulence. After 600 ms, P_m decreases sharply, probably because of settling of the dust. In contrast to P_m, $(dP/dt)_m$ decreases quite sharply in the 0 - 200 ms region (see Fig. 11), because this parameter is strongly dependent on the quantity of turbulence. There is a plateau from about 200 - 600 ms, similar to P_m, then a sharp drop after 600 ms.

From these results, it can be seen that a delay time of 100 ms is not unreasonable for most work. A delay time of, say 400 ms, will provide a low turbulence value of P_m and $(dP/dt)_m$, but it must realized that the reaction may not be as complete. The steep dependence of the $(dP/dt)_m$ for short delay times explains the difficulty in obtaining reproducible values of this parameter. Hence, it is important to specify the delay time used for

any tests as well as to use the same delay time as much as possible.

According to the elemental analysis of lycopodium given by Hertzberg et al (11), stoichiometry occurs at about 130 g/m^3. Therefore, one would expect that most of the lycopodium should remain intact after the test. Qualitatively, as mentioned above, under standard conditions, most of the lycopodium appeared to have reacted. To resolve this paradox, a quantitative analysis of the residue left in the vessel after the explosion would be required. This would be a difficult procedure to carry out and was not attempted at this time. A possible explanation is that the high temperature reached during the explosion causes pyrolysis of the unreacted dust.

Effect of Concentration (Electrical Discharge Ignitor)

The explosion pressure rises rapidly with increasing dust concentration from the minimum explosible concentration to reach a broad plateau (see Fig. 12). The standard deviations are indicated by vertical bars. (No vertical bars are shown for single determinations.) At the lowest concentration studied, the flash from the explosion was noticeably weaker, lasted longer and consisted of tiny flamelets, rather than a homogeneous flash. The dependence of $(dP/dt)_m$ on concentration is similar to that of P_m (see Fig. 13).

In the Hartmann apparatus, the maximum for $(dP/dt)_m$ occurs at a lower concentration than P_m: about 200 g/m^3, compared to about 750 g/m^3. By contrast, in the 20-L vessel, the maxima of P_m and $(dP/dt)_m$ appear to occur at roughly the same concentration for lycopodium, which would seem to be more reasonable.

Using the pressure dependence to determine the minimum explosible concentration requires some judgement. Cashdollar and Hertzberg (4) define

the lower flammability limit (another term for the m.e.c.) as that concentration giving a pressure ratio of 2 (equivalent to 101 kPa in our system). Our results on lycopodium are consistent with this somewhat arbitrary definition: the tests carried out at 100 g/m^3 produced definitely marginal explosions.

Chemical Ignitor Tests

The electric arc is a relatively weak ignition source, and has been criticized for that. The International Standards Organization Standard ISO 6184/1 (3) calls for the use of two 5-kJ chemical ignitors in a test vessel of volume 1 m^3. This ignitor, made by Fr. Sobbe G.M.B.H., Federal Republic of Germany, with a built-in electric match, consists of 40% zirconium, 30% barium nitrate and 30% barium peroxide. The U.S. Bureau of Mines also uses this ignitor for dusts (such as sulphide ore dust) that will not ignite by an electric arc.

The Sobbe ignitor, based on its chemical composition, is very close to oxygen balance and thus should not consume any oxygen . It should produce a small amount of nitrogen, increasing the amount of nitrogen by about 0.2%. Experimentally, the oxygen analyzer showed no change in the oxygen concentration in the 20-L vessel after igniting a Sobbe ignitor. The pressure observed in the vessel after ignition is not due to an increase in the amount of gas, but to the very energetic reaction.

The dust explosion control panel (6) was designed with the capability of supplying current to the chemical ignitor as an alternative to energizing the transformer that creates the arc. For most of these tests, the chemical ignitor was hung from the electrodes in the centre of the 20-L vessel facing downwards. Later, a holder was made so that the chemical

ignitor could be held firmly in place.

One complication arising from the use of the ignitor is the additional pressure created by the reaction of these chemicals. The maximum of 51 kPa occurs 15 - 20 ms after firing. This effect must be taken into account when analyzing the data. To a good approximation, the explosion pressure for strong explosions can be determined simply by subtracting off the 51 kPa. However, for $(dP/dt)_m$, it is necessary to subtract the pressure trace due to the ignitor from the experimental pressure trace before taking the derivative. By downloading programs from the diskette into the oscilloscope mainframe, the experimental pressure trace can be aligned vertically and horizontally with the stored pressure trace of the chemical ignitor. This is illustrated in Fig. 14. (Note the expanded time base.) The derivative curve is then generated in the usual manner. The shapes of the derivative curves are shown in Fig. 15. Most of the leading shoulder, which is due to the chemical ignitor, has been removed by this process. The residual amount is due to slight errors in alignment and random variations. (Derivatives always accentuate differences between curves.) For weaker explosions, e.g. near-limit concentrations, this process becomes more important,not only fo determining $(dP/dt)_m$, but also for determining P_m. The uncorrected derivative curves of these tests can show two distinct maxima, the first due to the ignitor, the second due to the dust. The additional time required for analysis of each test using the above procedure is up to 1/2 hour.

In Figs. 12 and 13, the corrected values of P_m and $(dP/dt)_m$ from the chemical ignitor tests are shown as a function of concentration along with those determined by the electrical arc ignitor. For high concentrations (above 200 g/m^3), P_m is the same. However, for low concentrations, the

chemical ignitor produces much higher P_m. Essentially, the chemical ignitor is shifting the apparent m.e.c. to a lower value (about 30 g/m^3 vs. 100 g/m^3). It should not be assumed that progressively more powerful ignitors will produce lower and lower values of m.e.c. If an ignitor is too powerful for the given explosion vessel, there will be excess overdrive of the reaction and the measured pressure rise will not represent a true steady-state value.

The value of the m.e.c. for lycopodium of 30 g/m^3 obtained here is close to the value obtained by Bartknecht (10) of 32 g/m^3 using a 1 m^3 vessel. On the other hand, Bartknecht obtained a maximum explosion pressure of 690 kPa, which is well outside the experimental error of our value of 532 kPa. To overcome the problem of the dependence of $(dP/dt)_m$ on the size of the vessel, Bartknecht uses the cube-root law:

$$K_{st} = (dp/dt)_m \cdot V^{1/3}$$

where V is the volume (in m^3). Our K_{st} value for lycopodium (obtained using the chemical ignitor) is thus 92 bar·m·s, compared to 115 bar·m·s, obtained by Bartknecht. This difference is not a matter of concern, because of the great dependence of K_{st} on the degree of turbulence (see Fig. 11).

The validity of assuming that the measured pressure is simply the sum of that due to the ignitor and that due to the dust-air explosion may be questioned. Equilibrium thermodynamics obviously cannot be applied to an analysis of this system. It may be possible to do a theoretical treatment of an ignitor exploding in a flammable gas-air mixture, which may be sufficient to estimate the error in the pressure summation assumption. (A dust-air mixture would require additional assumptions on the rate of burning of the particles.) Unfortunately, the writer does not have the time for that.

Instead, the fact that the corrected explosion pressures at high concentrations for the chemical ignitor tests are the same as the pressures from the arc discharge tests, will be used as an empirical justification for the assumption.

It may be thought that the fact that the explosion pressure of lycopodium is the same at two different initial pressures (the ignition of the lycopodium beginning when the chemical ignitor has raised the pressure in the vessel by about 51 kPa) contradicts the previous section in which explosion pressure was shown to increase linearly with initial pressure. However, the total amount of oxygen in the vessel (which determines the amount of reaction and thus the pressure) is the same for both the ignitor and arc tests.

Unfortunately, the values of $(dP/dt)_m$ for the chemical ignitor are significantly greater than those for the arc ignitor at all concentrations. Referring back to Fig. 11, the strong dependence of $(dP/dt)_m$ on the turbulence level (the inverse of the delay time) can be noted. Perhaps the chemical ignitor creates additional turbulence. Referring to Fig. 14, it can be seen that $(dP/dt)_m$ occurs (for lycopodium) in the same region as the maximum pressure of the chemical ignitor. For dust-air explosions that have a longer induction time than lycopodium, this concept leads to the prediction that there should be closer agreement between arc and ignitor for $(dP/dt)_m$.

The error limits for the chemical ignitor tests are much smaller than those for the electric arc tests. Presumably, this is because it is difficult to create and maintain a reproducible arc.

Very recently, Zhu et al (9) have published a paper showing that the chemical ignitor in a plastic shell (the same as we used here) produced smaller P_m and $(dP/dt)_m$ than the same composition packed in a metal shell

in tests on maize and aluminum dust in the 20-L vessel. The difference was attributed to a faster rate of release of energy with the metal shell ignitor.

For comparison, the pressure trace of the chemical ignitor that we are using was recorded using the Nicolet oscilloscope, sampling every 50 μs (see Fig. 18). Neglecting, for the present, the high frequency oscillations, it can be seen that the pressure rises steeply at first. attaining half its maximum in about 2 ms, and reaching its maximum in about 15 ms. Zhu's graphs show a more irregular rise, particular for the plastic shell ignitor: the metal shell ignitor attains half its rise in about 2 ms and its maximum value in about 4 ms; the plastic shell ignitor attains half its value in about 12 ms and its maximum in 32 ms.

Returning now to the oscillations, the measured frequency is about 1500 Hz in the initial part of the curve, decreasing to about 900 Hz later, compared to Zhu's values of 10 000 Hz for the metal shell ignitor and 300 Hz for the plastic shell ignitor. Assuming that the oscillation arises strictly from reflected pressure waves, then the frequency should be about 600 Hz. Since the ignitor is placed centrally, the frequency should be twice that, or 1200 Hz while the ignitor is still reacting. It appears that our values are in the right range; Zhu's values cannot be interpreted by this model.

The importance of disputing Zhu's work is his finding that the explosion pressure can be a strong function of the construction of the ignitor. Our work reported above is not in accord with that finding. Even the use of completely different ignitors of considerably different energies (electric discharge vs. chemical ignitor) yielded the same explosion pressures (at concentrations well above the minimum explosible concentration). On theoretical grounds, the explosion pressure should be

more associated with the amount of reaction, and thus not be very dependent on the degree of turbulence.

Over the years, there has been considerable discussion in this laboratory whether piezoelectric or strain-gauge pressure transducers should be used for the study of explosions. The main argument against the latter is their slower response. The results above indicate that, except possibly for detonations, the strain-gauge transducers will produce an accurate pressure trace, considering that dust explosions are at least an order of magnitude slower than the ignitor.

Minimum Oxygen Concentration

An oxygen analyzer connected to the 20-L vessel allows measurement of the oxygen after the explosion test (7). It also enables tests to be carried out at concentrations of oxygen at other than that in the normal atmosphere. This application is particularly useful for determining the inerting level required to prevent the possibility of explosion, i.e. the minimum oxygen concentration.

The procedure used is to prepare a mixture by partial pressures in the air chamber using nitrogen, oxygen and/or air from compressed gas cylinders. After allowing sufficient time to mix, the actual oxygen concentration in the air chamber is measured (using the oxygen analyzer) prior to the test. After the test, the 20-L vessel is allowed to cool down and then the gas mixture is pumped through the analyzer.

The results of explosion tests on lycopodium (at a concentration of 500 g/m^3) with various concentrations of oxygen are shown in Figs. 16 and 17. Both graphs show that, for lycopodium at least, the minimum oxygen concentration (m.o.c.) is a very well-defined quantity (13.3%).

In particular, the change in explosion pressure is quite small until very close to the m.o.c. This is due to the explosion pressure being related primarily to the quantity of reaction, which does not change substantially until close to the m.o.c. (The concentration of oxygen in the post-explosion atmosphere varied between 0.1 and 1.1%.). Since the tests were carried out on the fuel-rich side, the amount of reaction possible decreases proportionately with the concentration of oxygen. Making the assumption that the explosion pressure is directly proportional to the amount of reaction, and using the 20.9% O_2 tests as the base value, we can predict the explosion pressure as a function of the oxygen concentration, which is the straight line shown in Fig. 16.

On the other hand, the rate of pressure rise is a strong function of the oxygen concentration. Part of the decreasing $(dp/dt)_m$ at lower oxygen concentrations may be due to a lower degree of turbulence at the time of ignition. For lycopodium in air, ignition occurs very soon after the electrical discharge starts. At progressively lower concentrations, the induction time becomes longer and longer, up to 180 ms. Fig. 11 shows the substantial effect that a longer delay time has on $(dp/dt)_m$. There remains, however, a portion of this decrease which must be attributed to an intrinsic decrease in the violence of the explosion.

Bartknecht (10) has reported a value of about 8.5% for the m.o.c. of lycopodium in his 20-L vessel (which differs somewhat in design from the USBM design). This value is significantly lower than the value of 13.3% obtained here. Interestingly, he has found "the oxygen concentration determined in the 1-m^3 vessel is 64% higher than the one determined in the 20-L laboratory sphere", which would would bring the m.o.c. for lycopodium into close agreement with our value obtained in the 20-L vessel. He attributes

the vast difference to the different strengths of ignitors. He uses the values obtained in the 1-m^3 vessel for recommendations for industrial design. This is an area worthy of further study, because of the importance of being able to predict accurately the quantity of inerting required.

CONCLUSIONS

The tests carried out show the importance of accurately defining the experimental parameters of dust explosion testing, in order to obtain meaningful data. Comparison with other workers must carefully consider the effects that small changes in apparatus or procedures may have on the explosion parameters. Of particular importance are the effects of initial pressure on the explosion pressure, the degree of turbulence on the maximum rate of pressure rise, and the strength of the ignitor on the minimum explosible concentration.

In our 20-L system, it is recommended that standard tests be carried out with an initial pressure as close to 101 kPa absolute as possible; that the experimental P_m and $(dP/dt)_m$ values be adjusted to 101 kPa, using the linear relationship, that the chemical ignitor be used for determination of the m.e.c. and the electrical arc be used for P_m and $(dP/dt)_m$ (for dusts ignitable by it). Measurement of the oxygen concentration provides a useful check on the completeness of the reaction and should be carried out routinely.

The discrepancies in the minimum oxygen concentration should be studied further, both in the 20-L vessel and in larger vessels. Analyses of the post-explosion gases and the residues is another area worthy of study.

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Table 1. Reproducibility of Tests on Lycopodium in 20-L Vessel (500 mg/L)

	P_i (kPa)	t_d (ms)	P_m (kPa)	t_m (ms)	$(dP/dt)_m$ (Mpa/s)	t_r (ms)	t_r/t_m
1.	95	122	515	94	11.9	58	0.62
2.	--	105	515	88	13.3	48	0.55
3.	--	115	540	98	13.1	56	0.57
4.	97	116	542	88	13.7	51	0.58
5.	98	110	563	93	14.8	61	0.66
7.	95	108	507	92	13.8	55	0.60
8.	98	100	558	92	15.9	63	0.68
9.	97	115	540	87	14.5	53	0.61
10.	97	116	515	105	11.9	64	0.61
mean			532	93	13.5	57	0.61
standard deviation			20	5	1.4	5	0.04

Notes: P_i - pressure due to air pulse

t_d - time between end of air pulse and beginning of pressure rise due to explosion

P_m - explosion pressure (total pressure minus P_a)

t_m - time from beginning of pressure rise to maximum pressure

$(dP/dt)_m$ - maximum rate of pressure rise

t_r - time from beginning of pressure rise to maximum rate

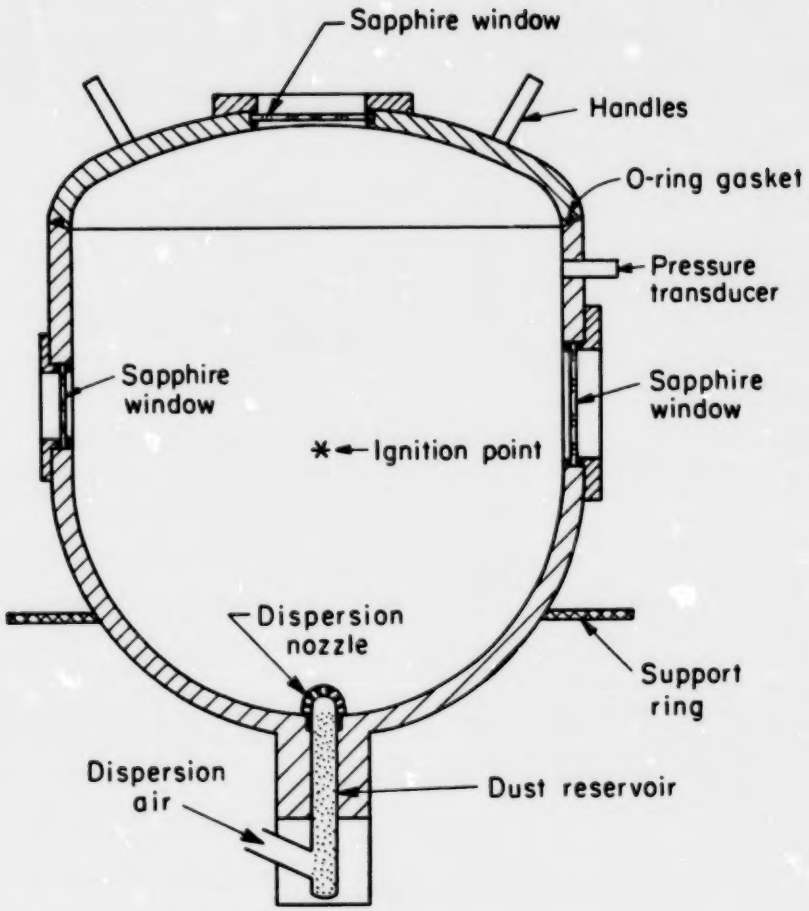


Fig. 1. Cross-section view of the 20-L vessel

Fig. 2. Photograph of the 20-L equipment

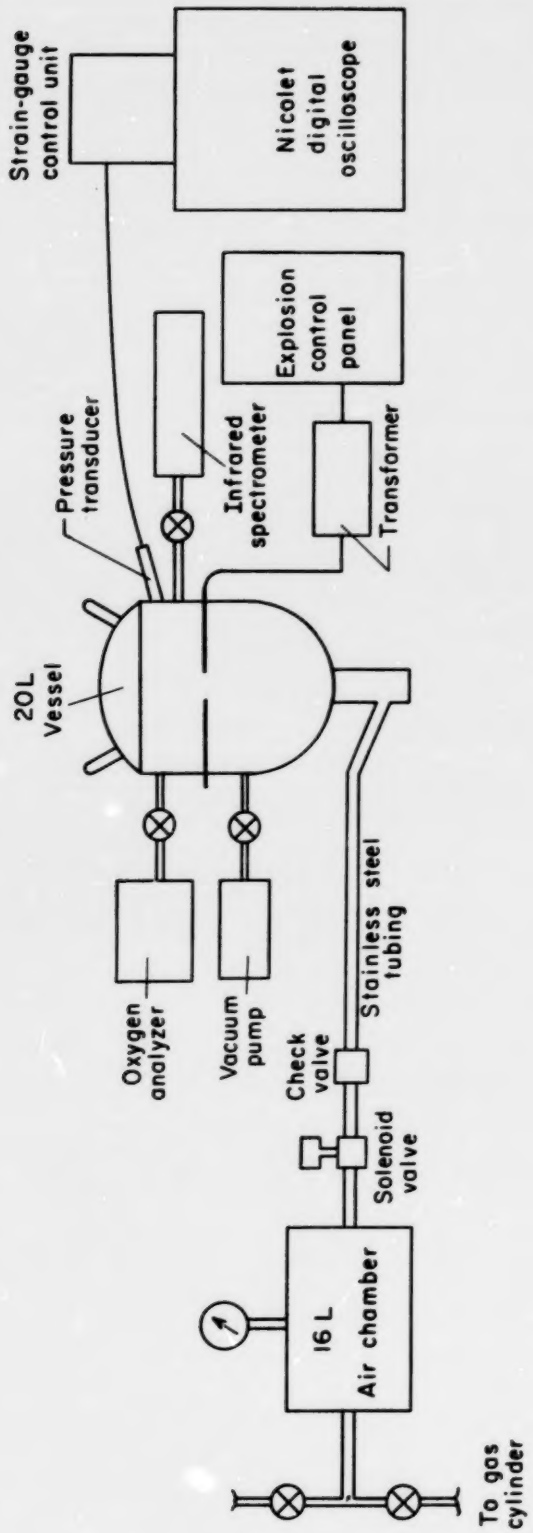


Fig. 3. Schematic diagram of the apparatus used for dust explosion tests

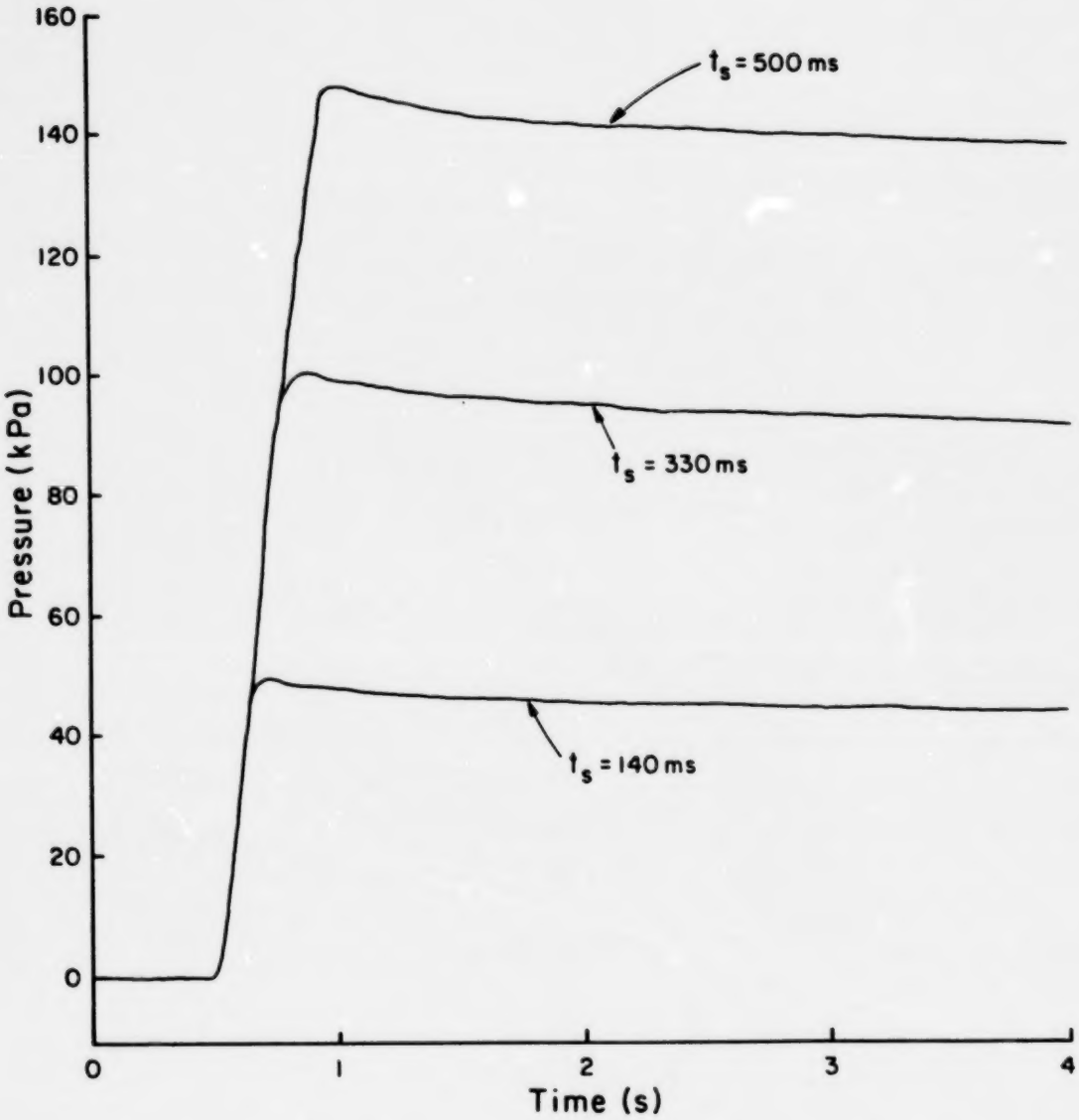


Fig. 4. Pressure trace with air only for three different solenoid open times

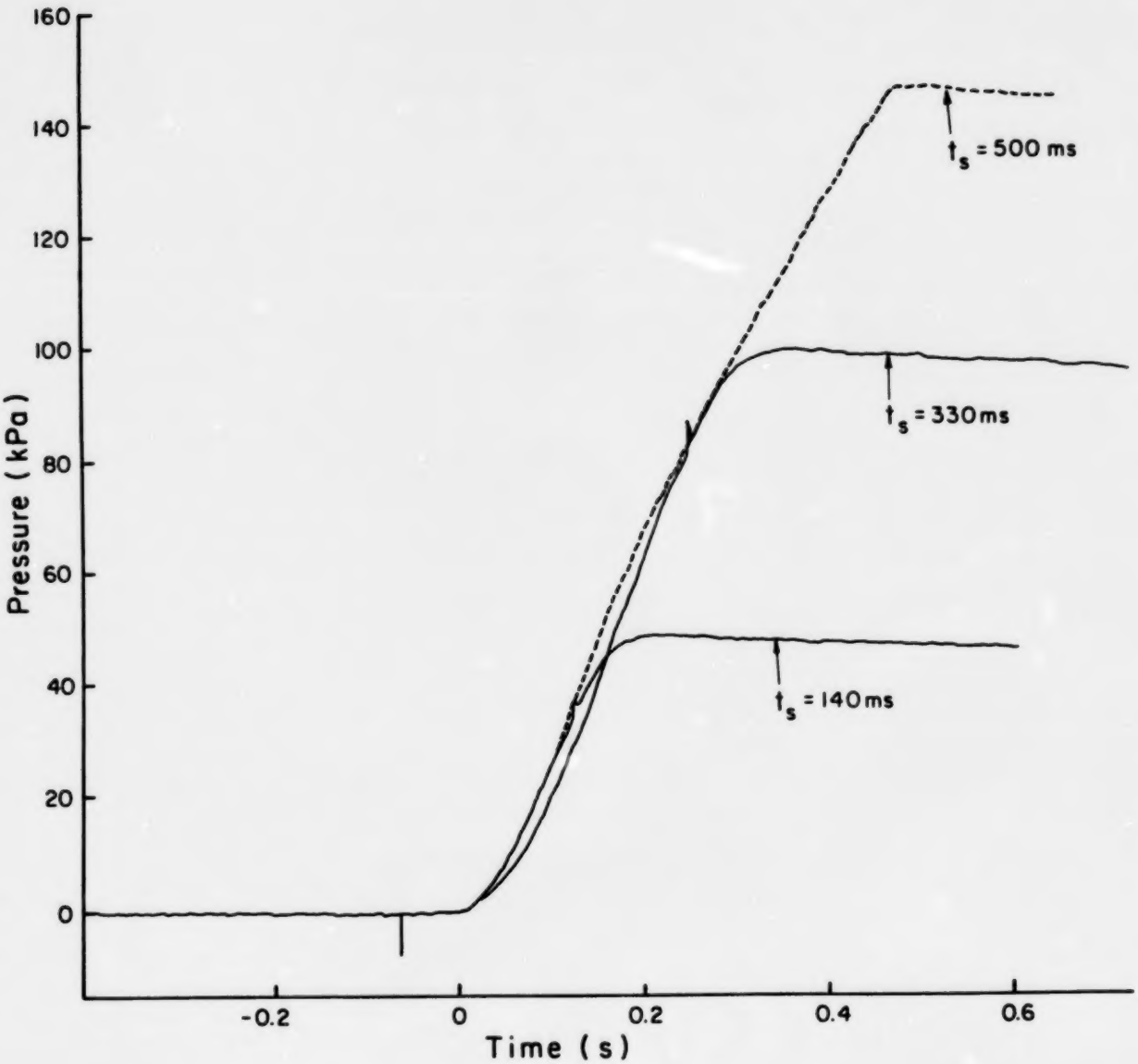
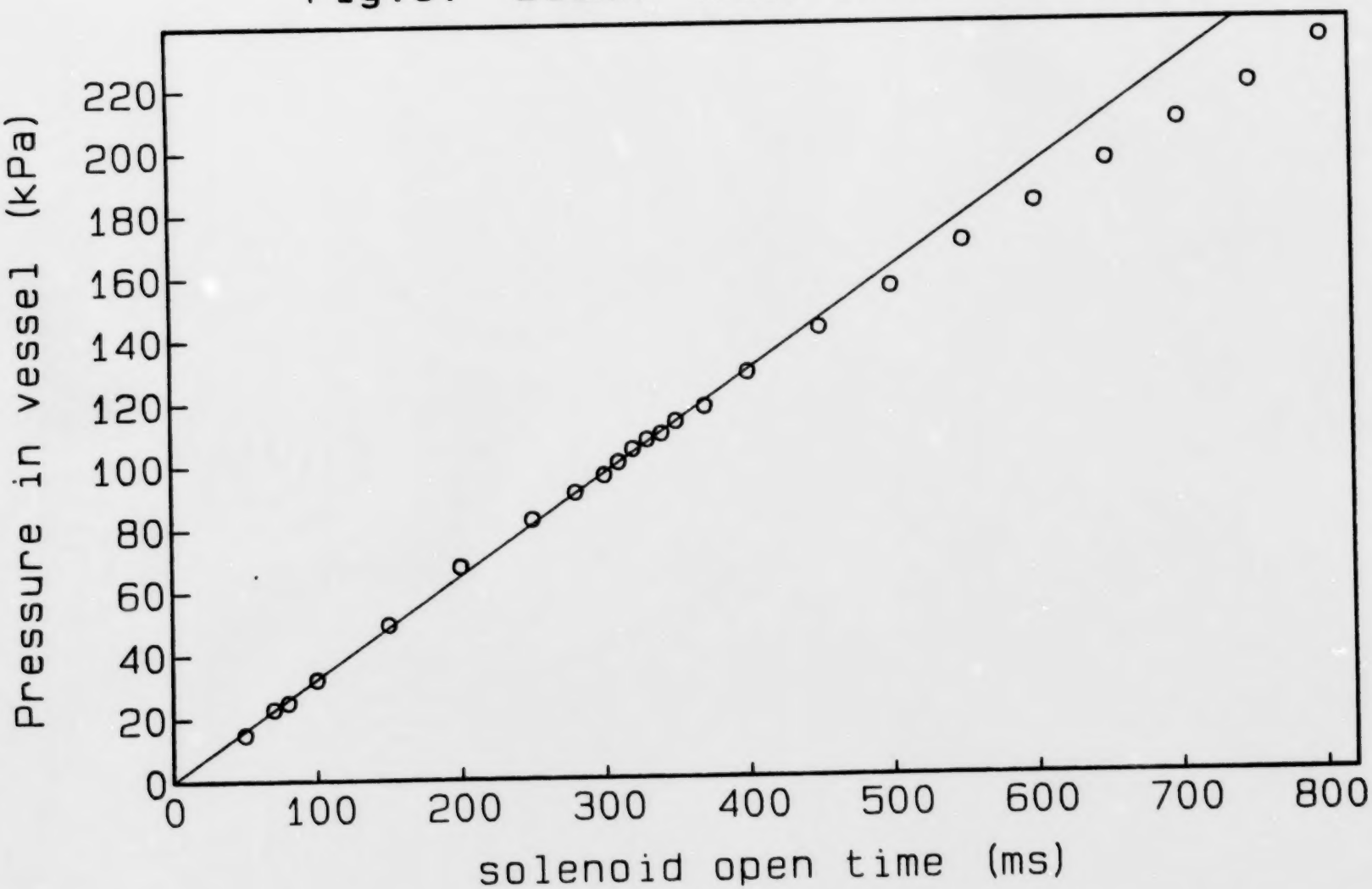


Fig. 5. Same traces as Fig. 4, but with the horizontal axis expanded to show more detail

Fig.6. "Blank" Runs in 20-L Vessel



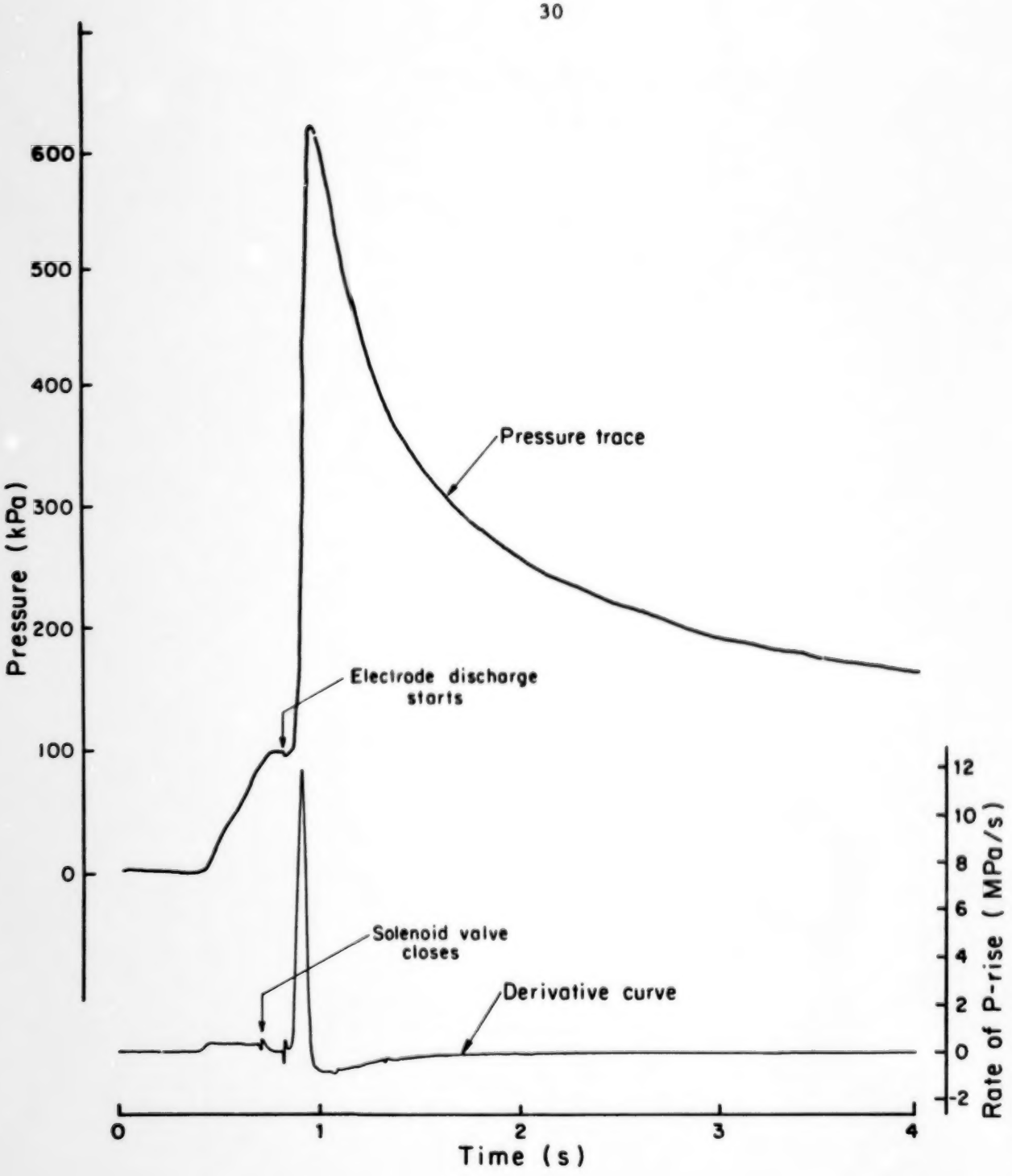


Fig. 7. Typical pressure trace and derivative curve for a lycopodium/air explosion at a concentration of 500 g/m^3.

Fig. 8. Effect of Initial Pressure

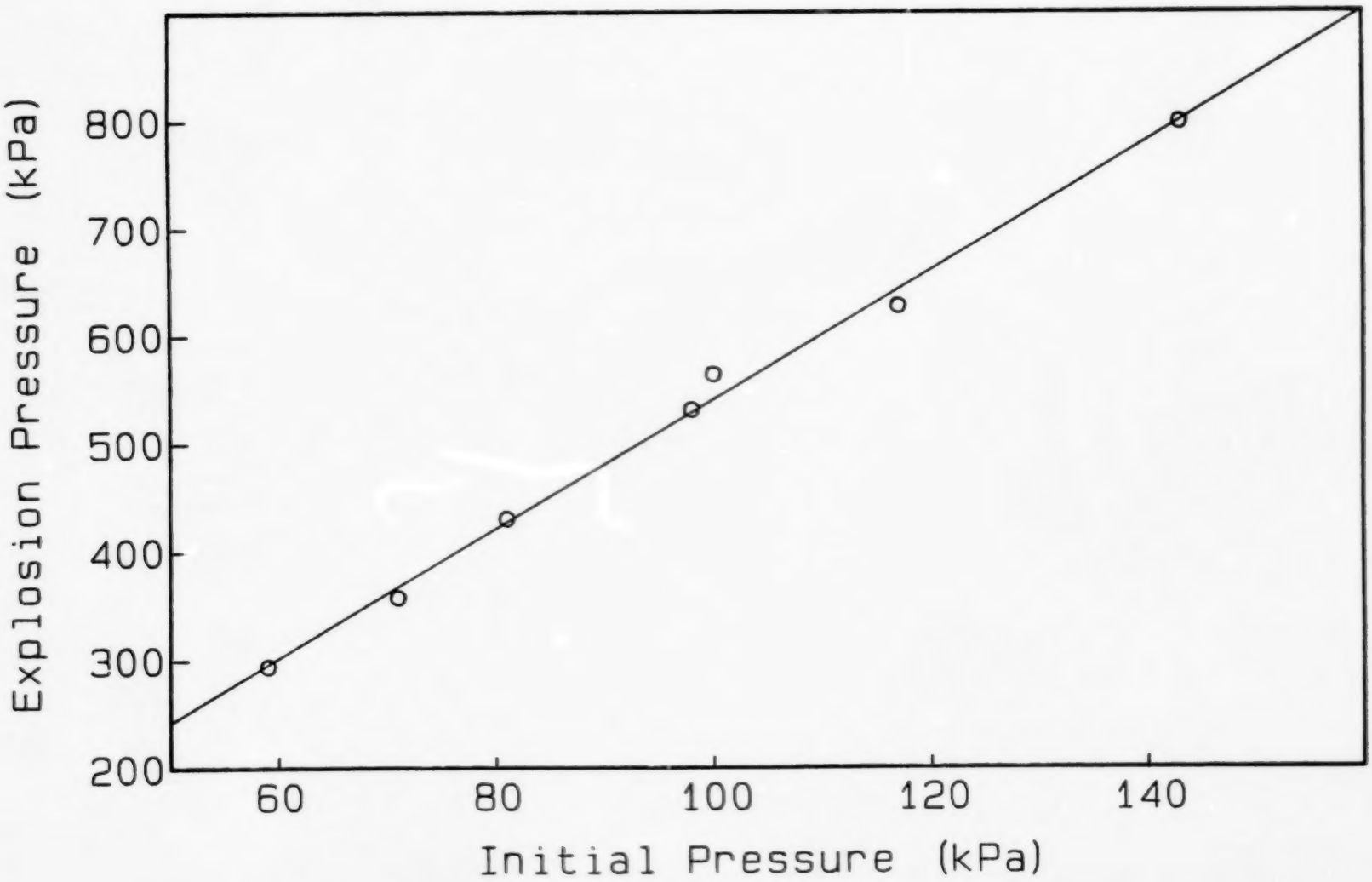


Fig. 9. Effect of Initial Pressure

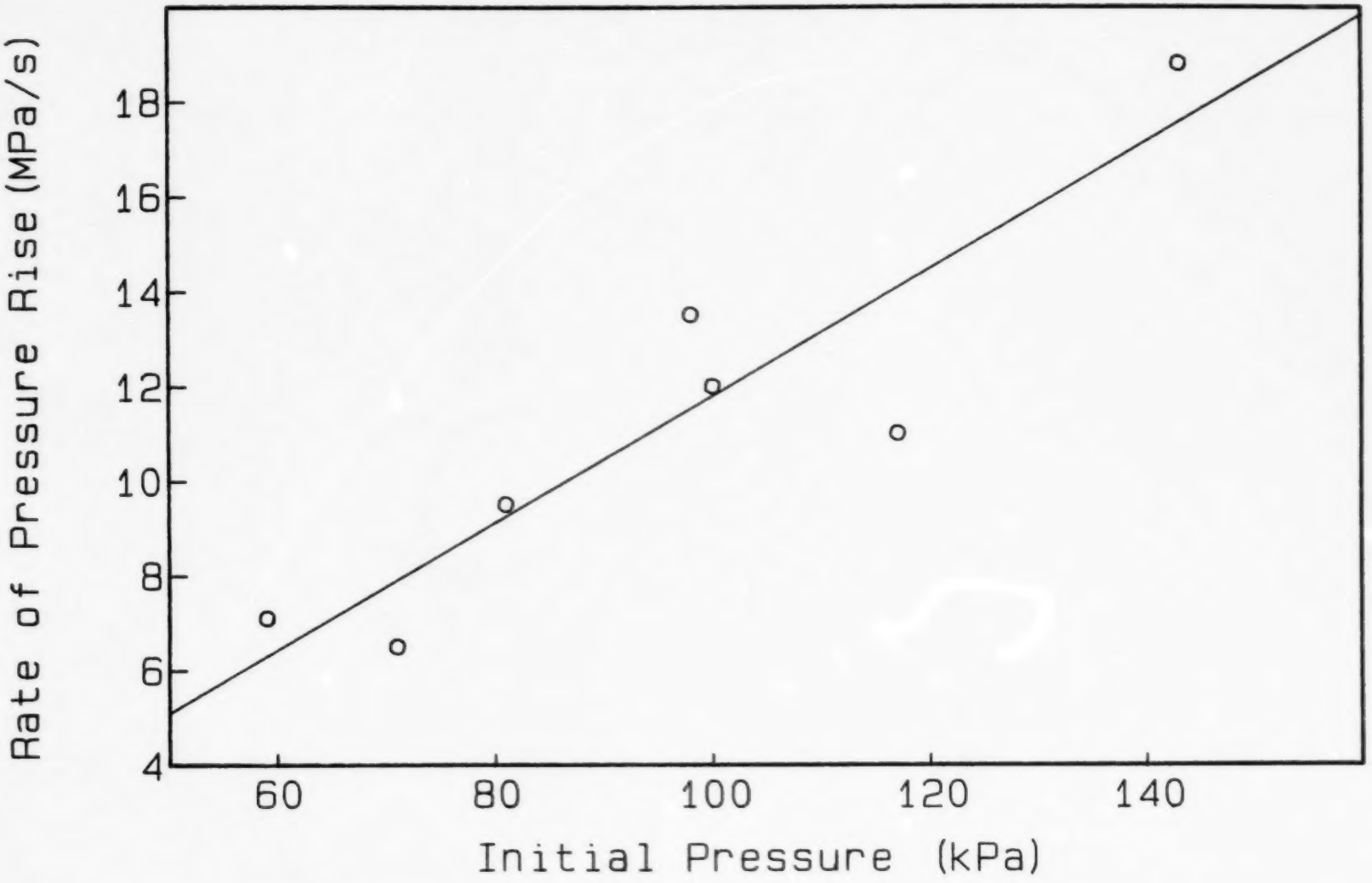


Fig. 10. Effect of Delay Time

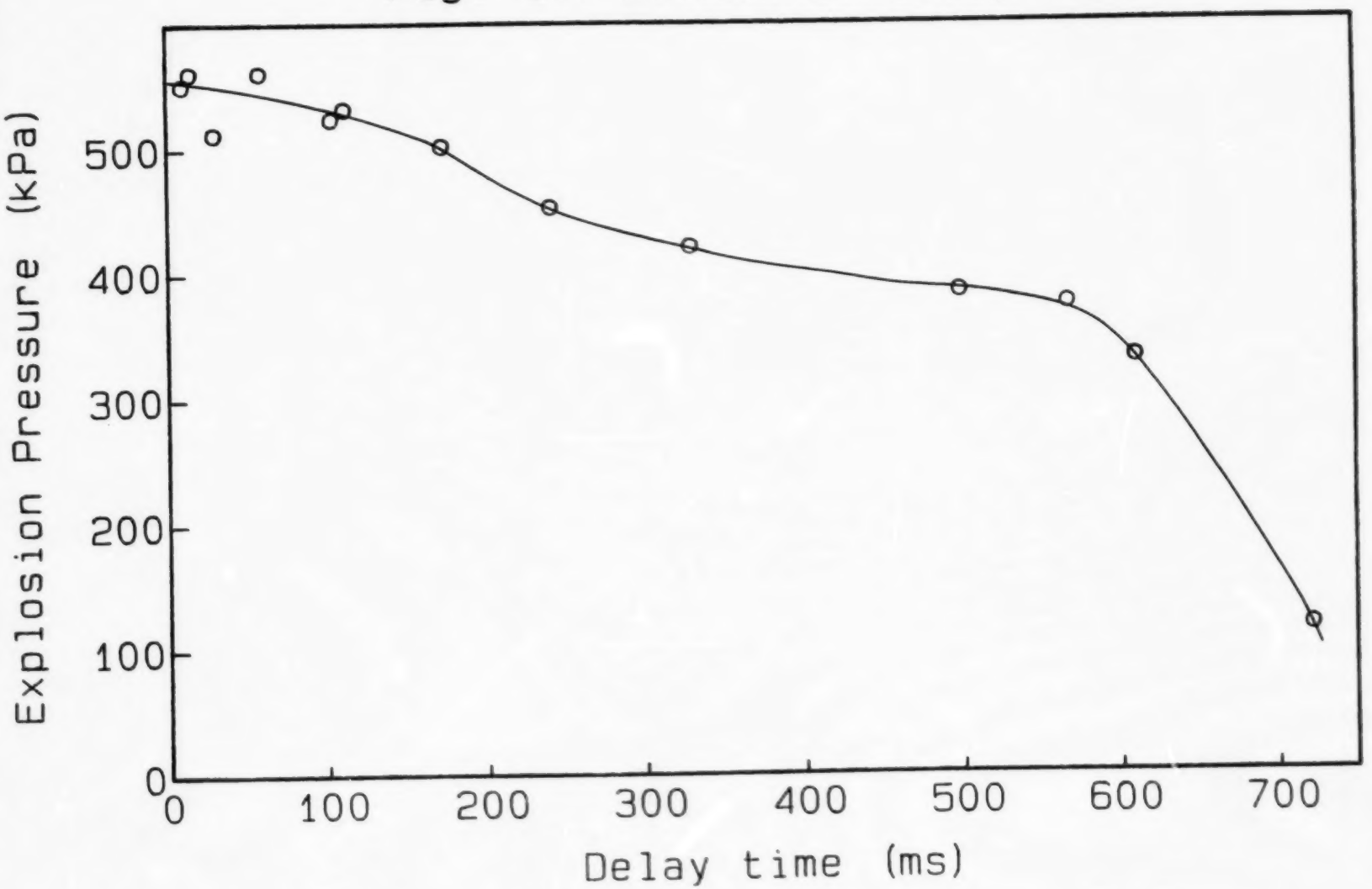


Fig.11. Effect of Delay Time

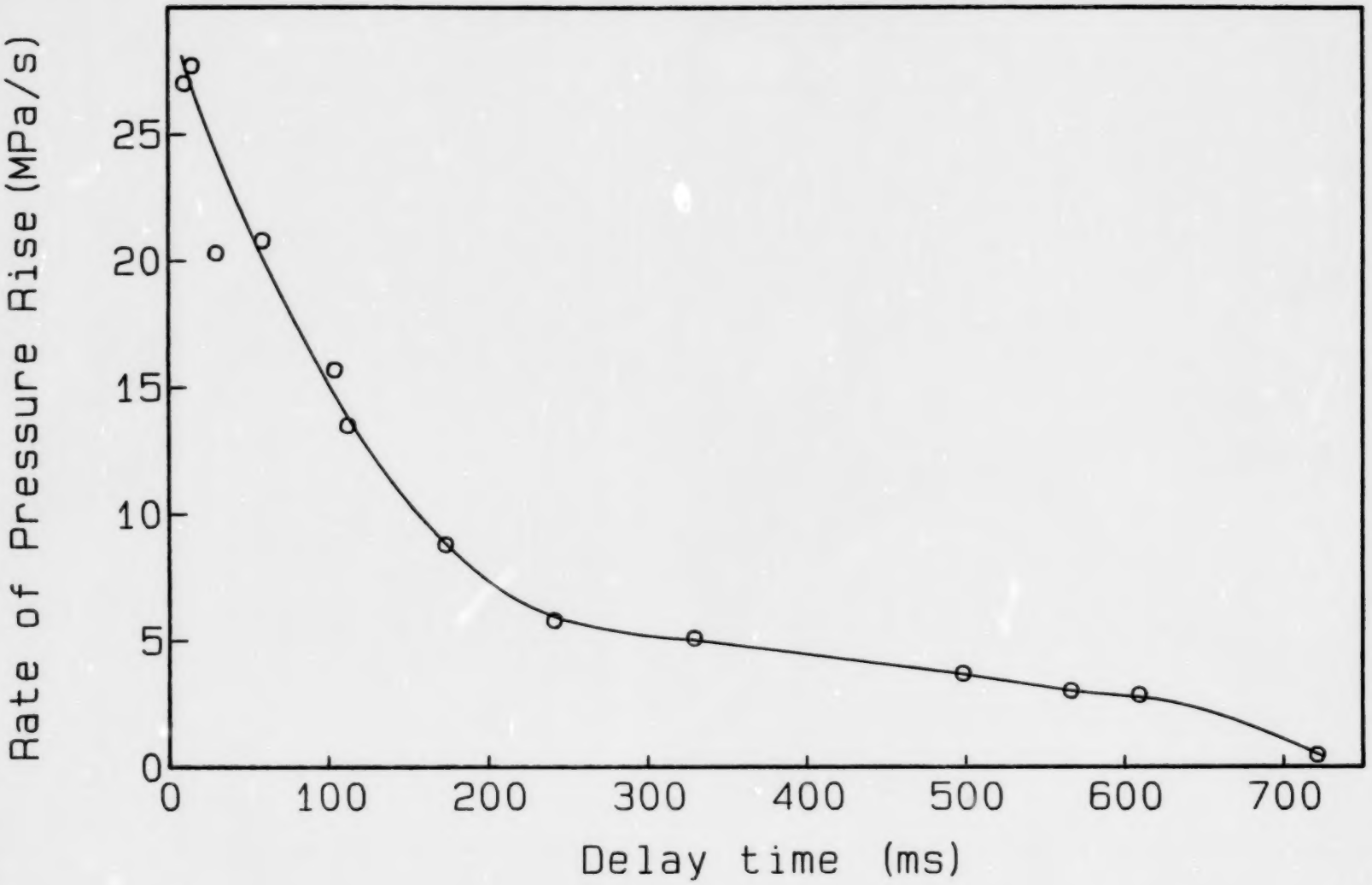


Fig. 12. Effect of Concentration

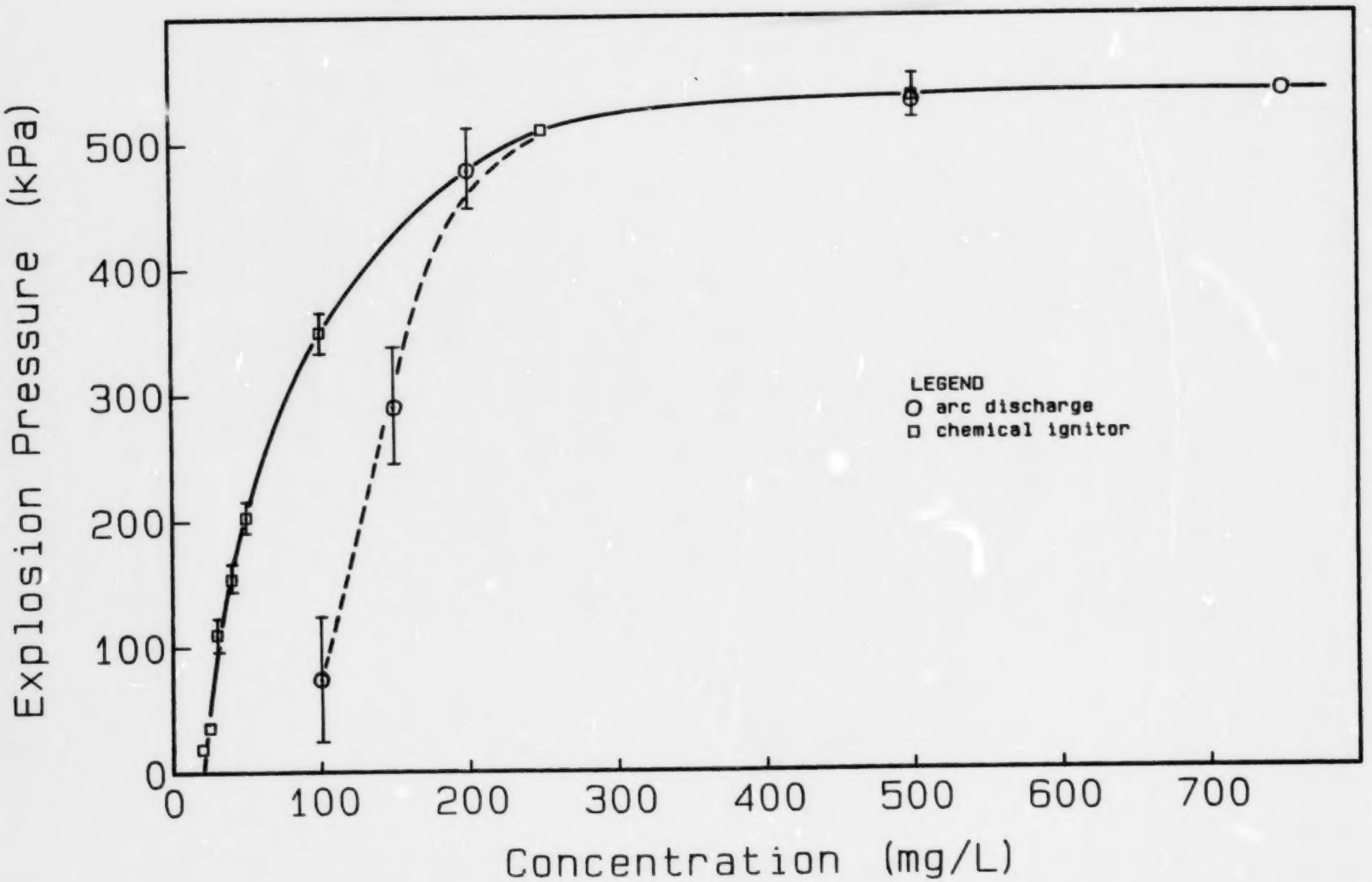
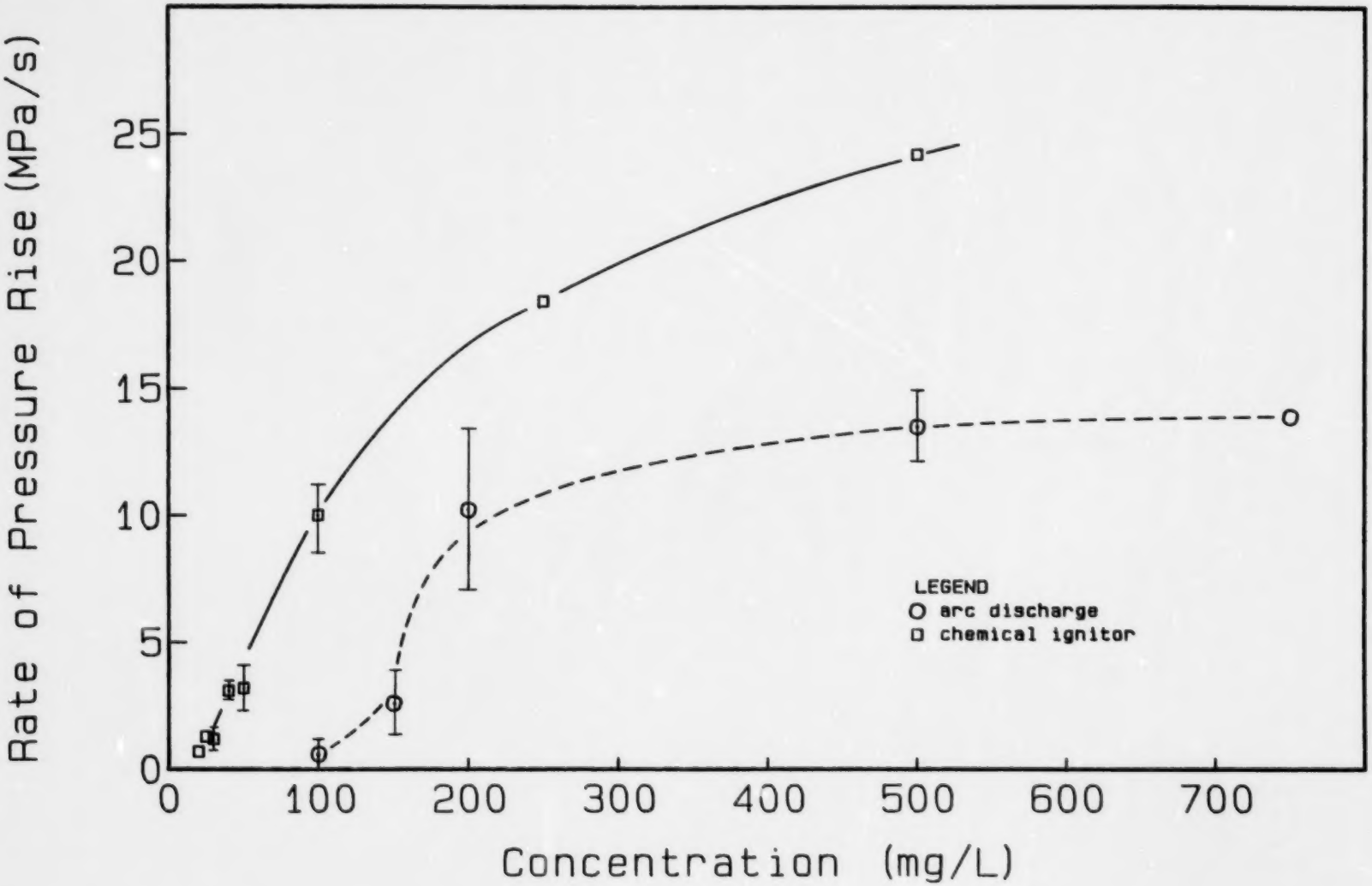


Fig. 13. Effect of Concentration



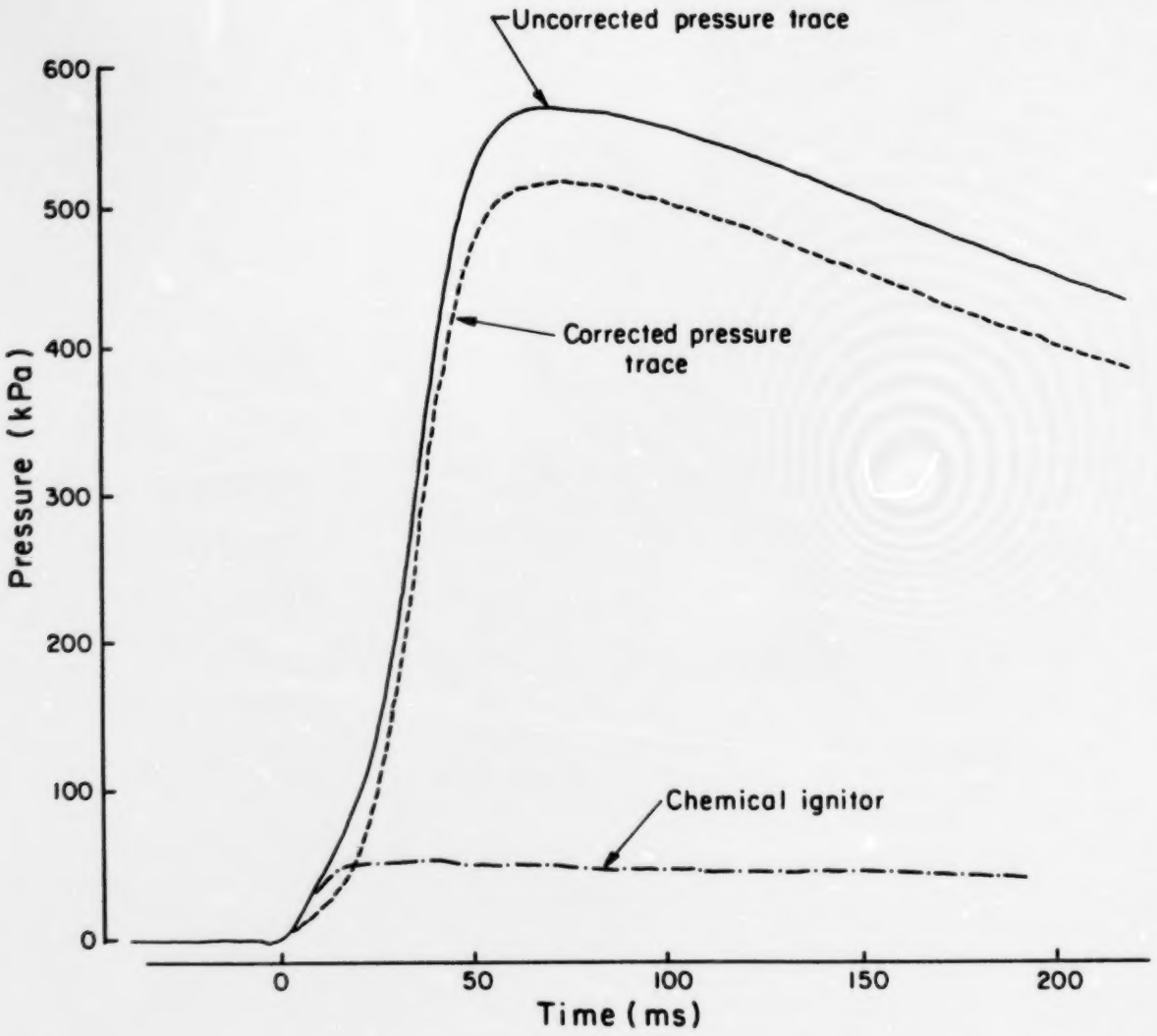


Fig. 14. Pressure traces of the ignition of the 5 kJ Sobbe chemical ignitor and a lycopodium/air explosion (concentration: 250 g/m^3) using the chemical ignitor

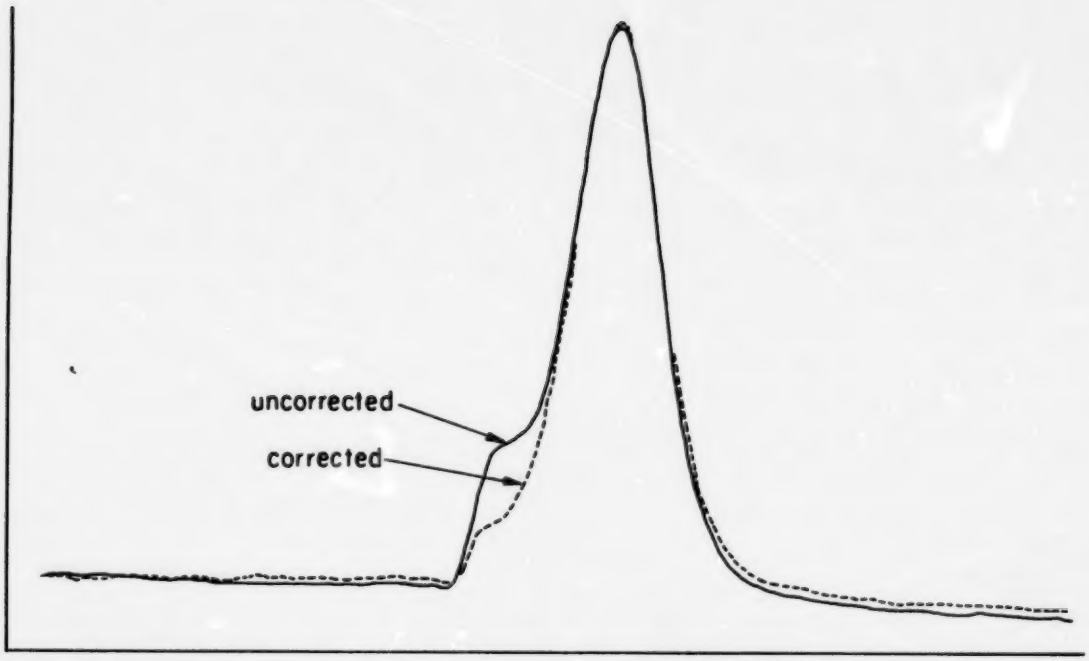


Fig. 15. The experimental and corrected derivative traces for the same lycopodium/air explosion as in Fig. 14.

Fig. 16. Explosion Pressure vs % Oxygen

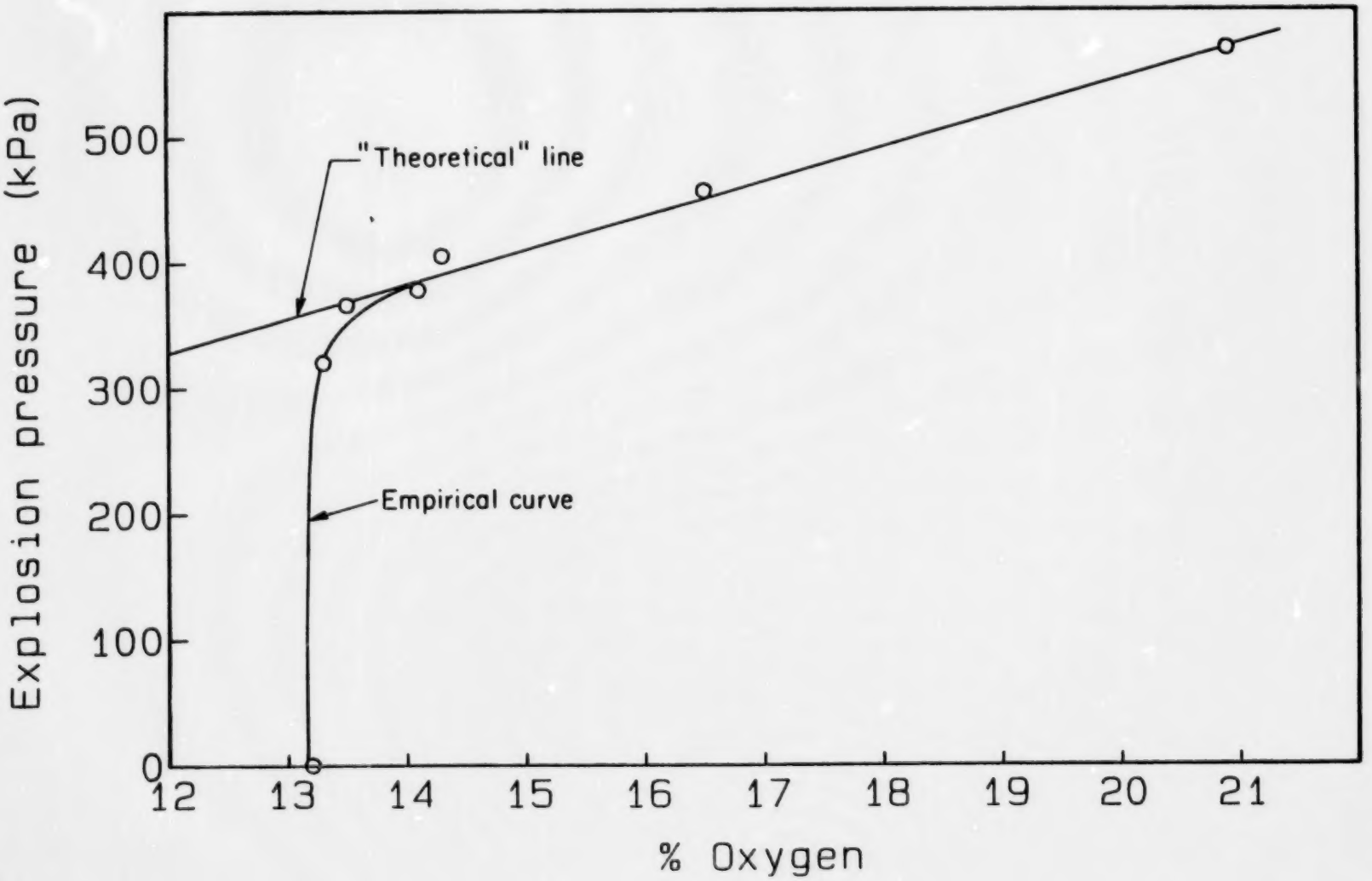
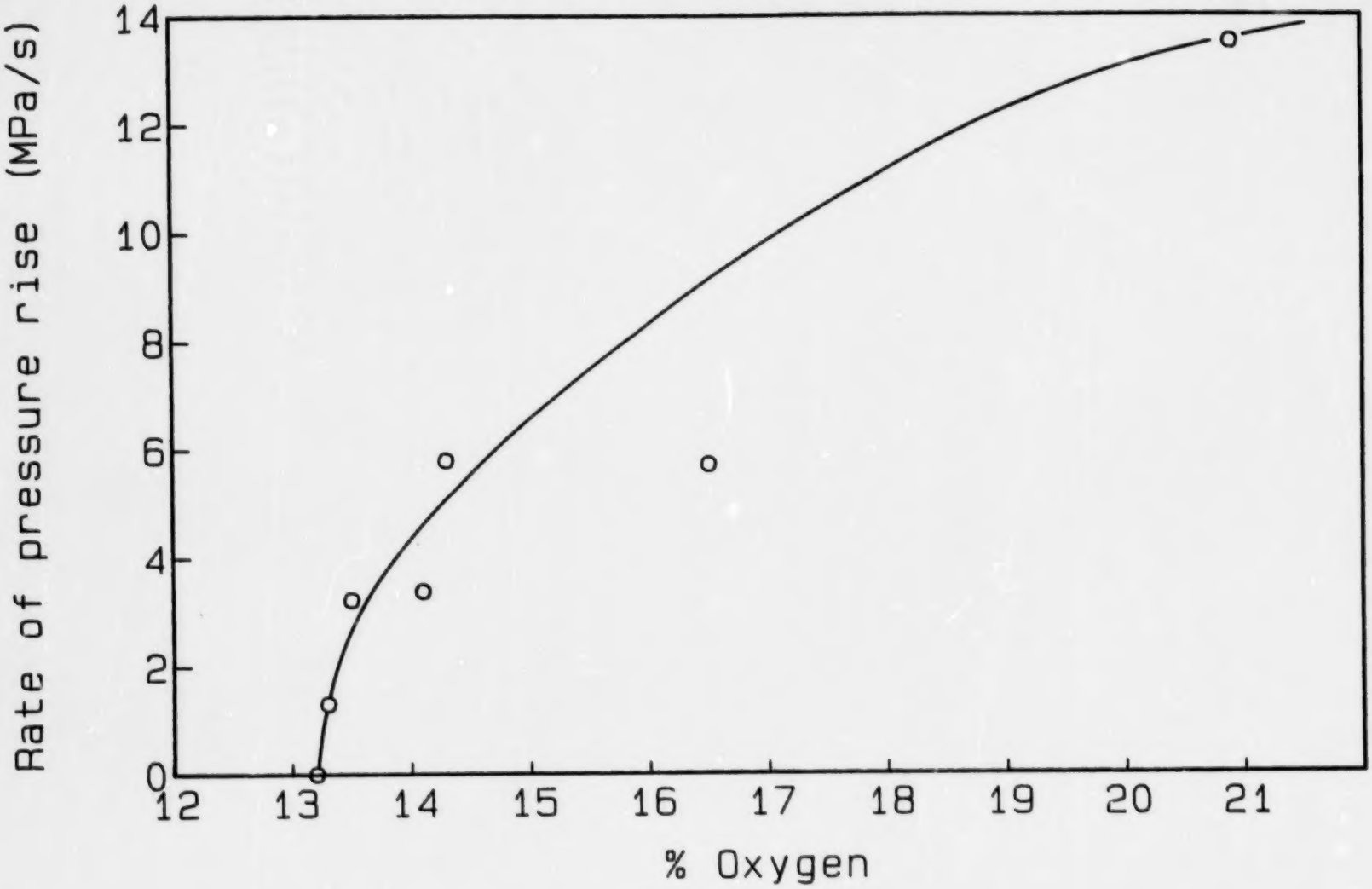


Fig.17. Rate of Pressure Rise vs % Oxygen



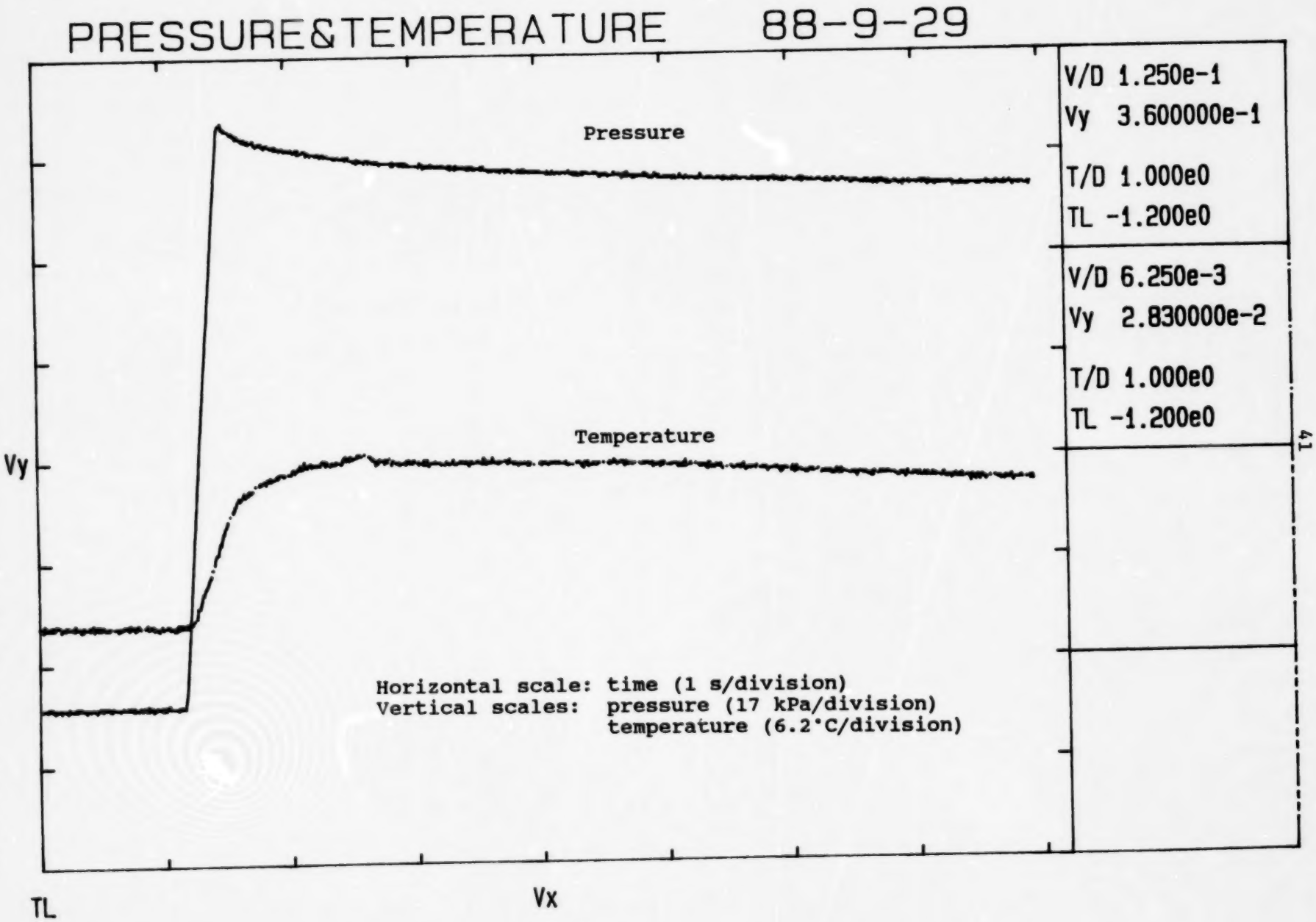


Fig. 18. Pressure and temperature traces for a standard air pulse entering the 20-L vessel

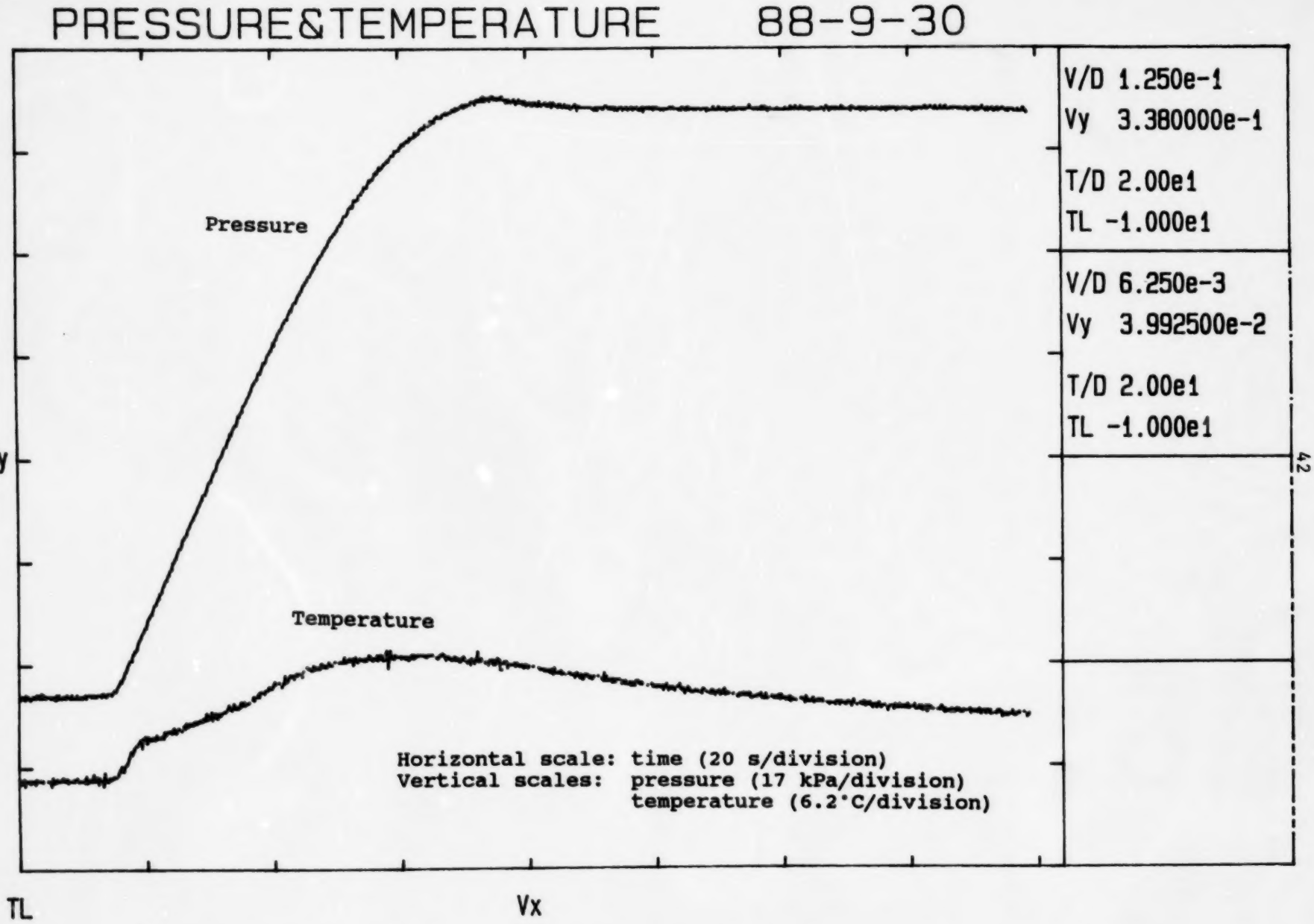
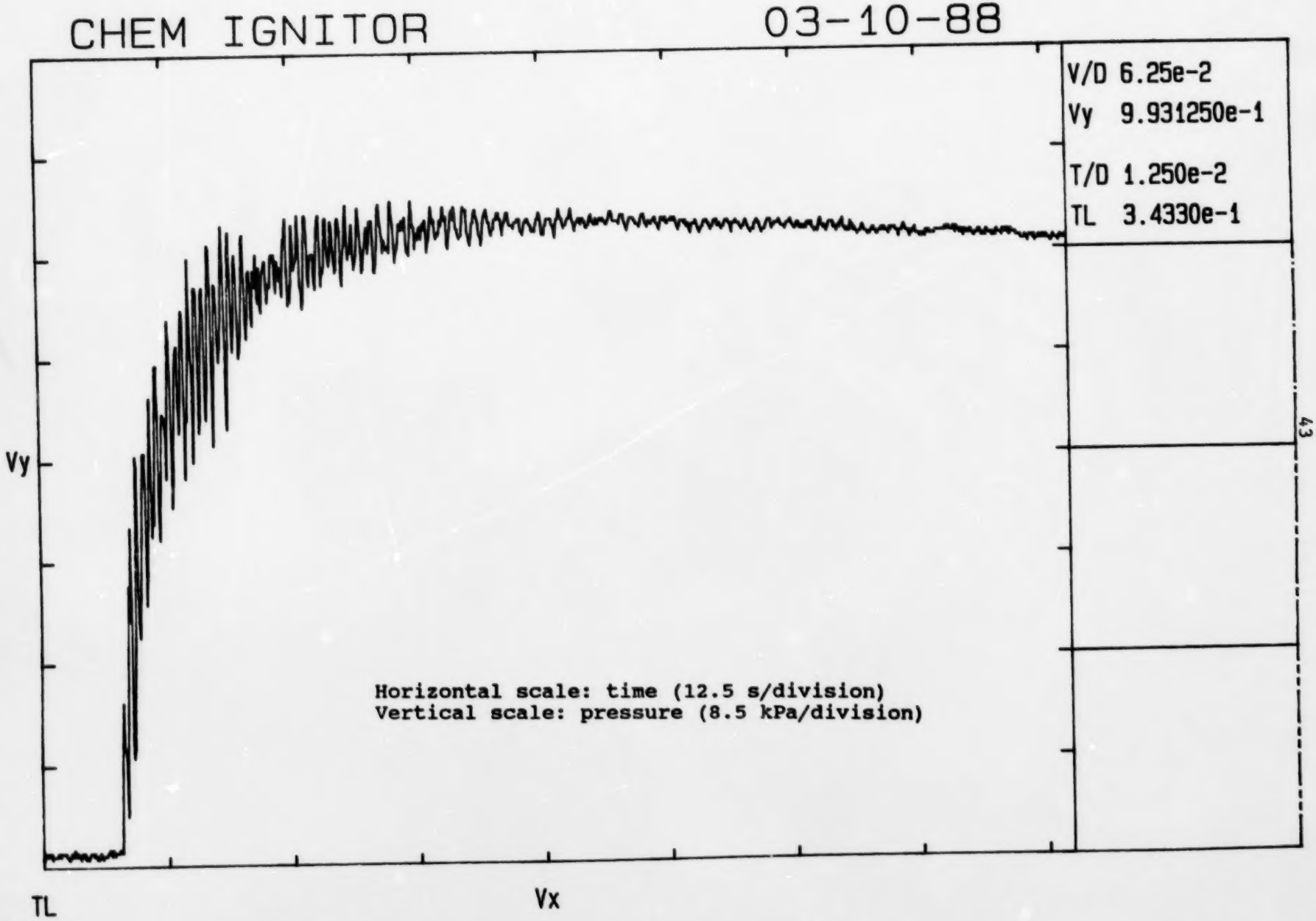


Fig. 19. Pressure and temperature traces for a very slow air entry into the 20-L vessel


CHEM IGNITOR
03-10-88
V/D 6.25e-2
Vy 9.931250e-1
T/D 1.250e-2
TL 3.4330e-1
Vy
TL
Vx
Horizontal scale: time (12.5 s/division)
Vertical scale: pressure (8.5 kPa/division)